Design Specifications for the 90° Dipoles for the Recycler Ring Electron Cooling Beamline

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The relativistic velocity of an 8 GeV kinetic energy antiproton is 0.9945. The electron beam must match this velocity so as to induce transverse momentum transfer from the antiprotons to the electrons, hence cooling the antiproton beam. Given the above relativistic velocity for the electrons, the rest of the kinematic parameters values have been calculated and are listed in table 1.

Table 1: Values for kinematic parameters of the electron beam used for electron cooling in the Recycler ring.

Parameter	Value
Relativistic Velocity	0.9945
Relativistic Energy	9.474
Relativistic Momentum	9.421
Rest Mass (MeV)	0.511003
Total Energy (MeV)	4.841
Kinetic Energy (MeV)	4.330
Momentum (MeV/c)	4.814

The purpose of the dipole magnets is to steer the electron beam around a racetrack which is approximately 66 m long. In one leg of the racetrack antiproton propagate through the same beam pipe for the purpose of momentum exchange with the electron beam. The geometry of the electron beamline is sketched in figure 1.

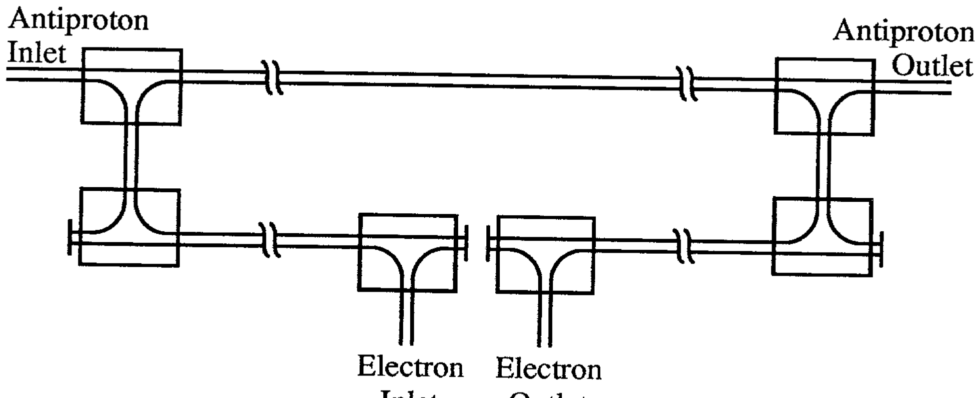

Figure 1: Sketch of the electron cooling beamline showing the entrance and exit points for both the electron and antiproton beams.

The 90° dipole magnets shown in figure 1 preferentially bend the electron beam due to the fact that the electron momentum is so much lower than the antiproton momentum. The relationship between radius of curvature and beam momentum for a given magnetic field is

$$B[\mathrm{kG}] = 33.356 \frac{P[\mathrm{GeV/c}]}{\rho[\mathrm{m}]} \quad . \qquad (1)$$

If the electron momentum and radius of curvature are specified, the magnetic field is determined. The effect of this magnetic field is to deflect the antiprotons by an amount given by the equation

$$\theta[\mathrm{mrad}] = 29.980 \frac{B[\mathrm{kG}]\ L[\mathrm{m}]}{P[\mathrm{GeV/c}]} \quad . \qquad (2)$$

The length L is the length of the magnet poles which the antiprotons see. Because the antiprotons are continuously bending while in the dipole magnet, they will also exit with an offset with respect to the original design orbit. The magnitude of the deflection is calculated using the relationship

$$\Delta x[\mathrm{mm}] = 500 \frac{L^2[\mathrm{m}]}{\rho[\mathrm{m}]} \quad . \qquad (3)$$

If a radius of curvature of 20" is chosen for the electron beam, the above equations can be used to specify the magnetic field of the dipoles, and hence their effect on the antiprotons. Table 2 contains a summary of all of these parameters for the dipoles, the electrons, and the antiprotons. Because of the fact that the antiprotons are deflected by approximately 1 mrad, a set of compensating dipoles must be placed on either end of the racetrack (outside of the racetrack). Assuming compensation dipoles with a magnetic field greater than 0.5 kG, the total offset of the electron cooling beamline with respect to the nominal orbit of the antiproton beam through that straight section is less than 1 mm.

Table 2: Values for kinematic and magnetic parameters of the electron and antiproton beams during electron cooling in the Recycler ring.

Parameter	Value
Electron Momentum (GeV/c)	0.004814
Electron Radius of Curvature (in.)	20
Electron Radius of Curvature (m)	0.508
Magnetic Field (kG)	0.316
Antiproton Momentum (GeV/c)	8.889
Antiproton Radius of Curvature (m)	938.3
Antiproton Magnetic Path Length (in.)	40
Antiproton Magnetic Path Length (m)	1.016
Antiproton Deflection Angle (mrad)	1.08
Antiproton Offset at Magnet Exit (mm)	0.550

The shape of the 90° dipole magnets is sketched in figures 2, 3, and 4 from different perspectives. The poles are flat except for shaped shims for improving the 2-D magnetic field quality seen by the antiprotons. If a 1" thick return flux is used, simple conservation of flux arguments predict that the field in steel will be less than 2.5 kG. Therefore, thinner flux returns (even 1/4") might be possible if sufficient mechanical rigidity can be achieved. Since almost full magnetic brick packing is required to achieve 1 kG in a 2" gap in the standard gradient magnets, it is estimated that full packing is required to achieve the required field of 0.3 kG in a 6" gap.

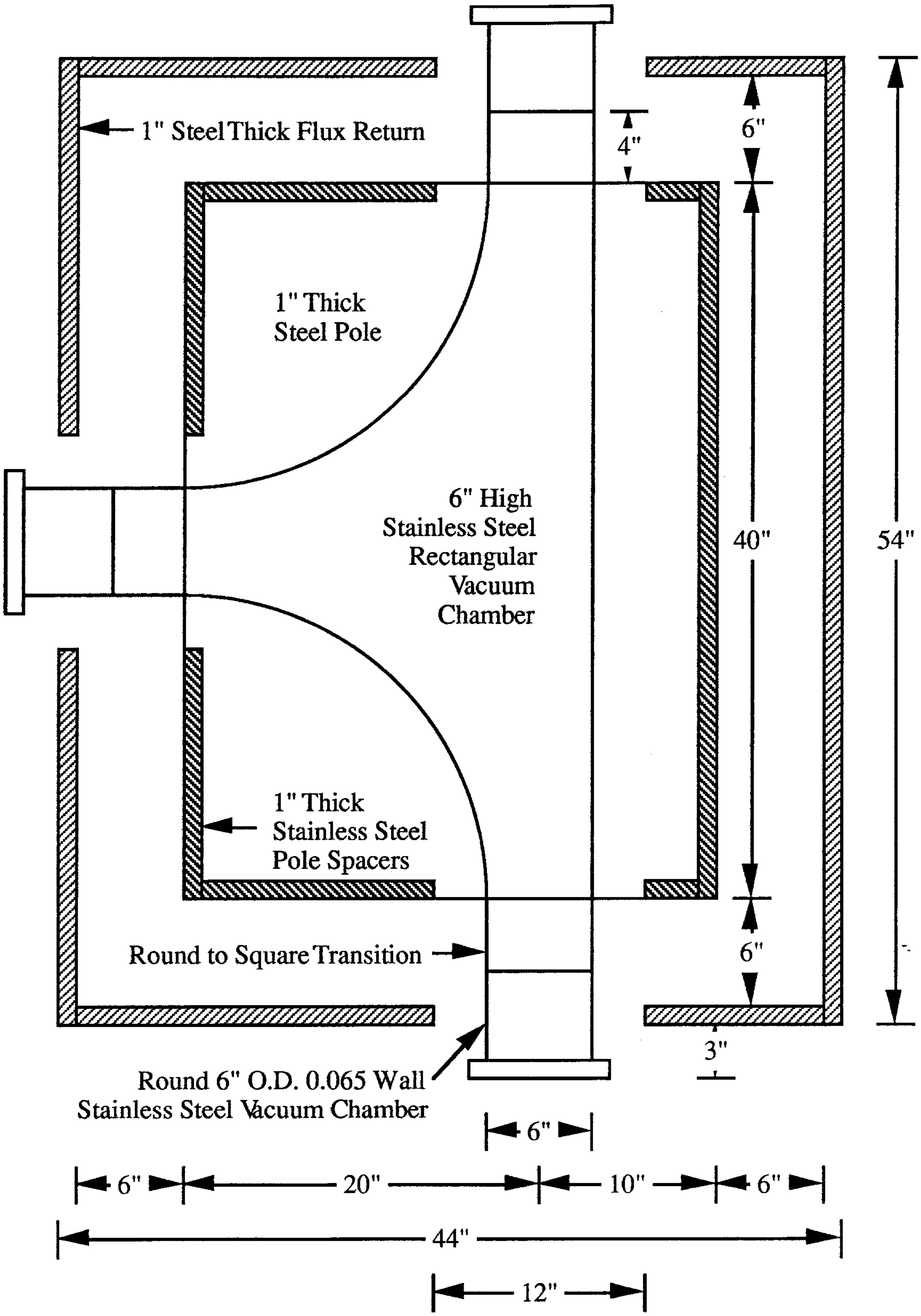

Figure 2: Top view of the magnet and the stainless steel vacuum chamber.

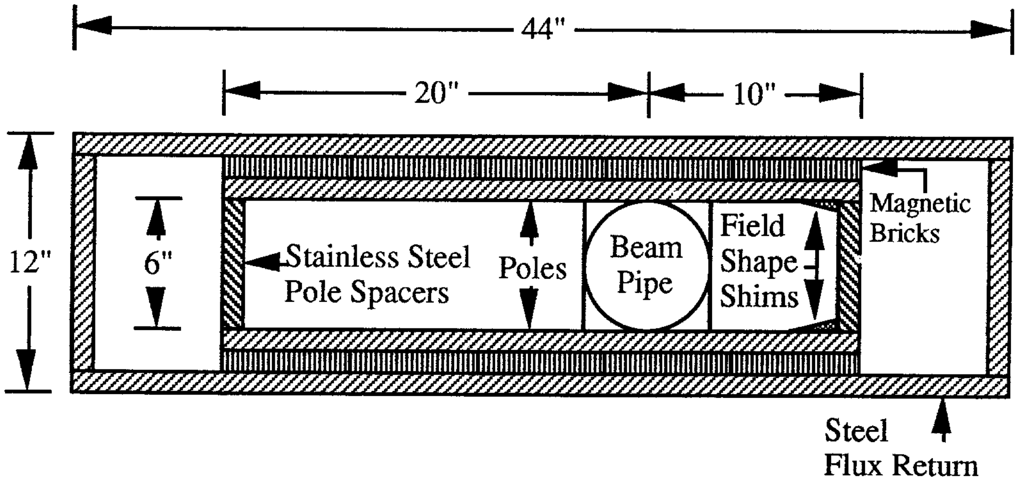

Figure 3: Antiproton inlet view of the dipole magnets showing the bricks stacked on either side of the poles in their 6" orientation. Note that field shaping shims were added to make the field the antiprotons see more uniform.

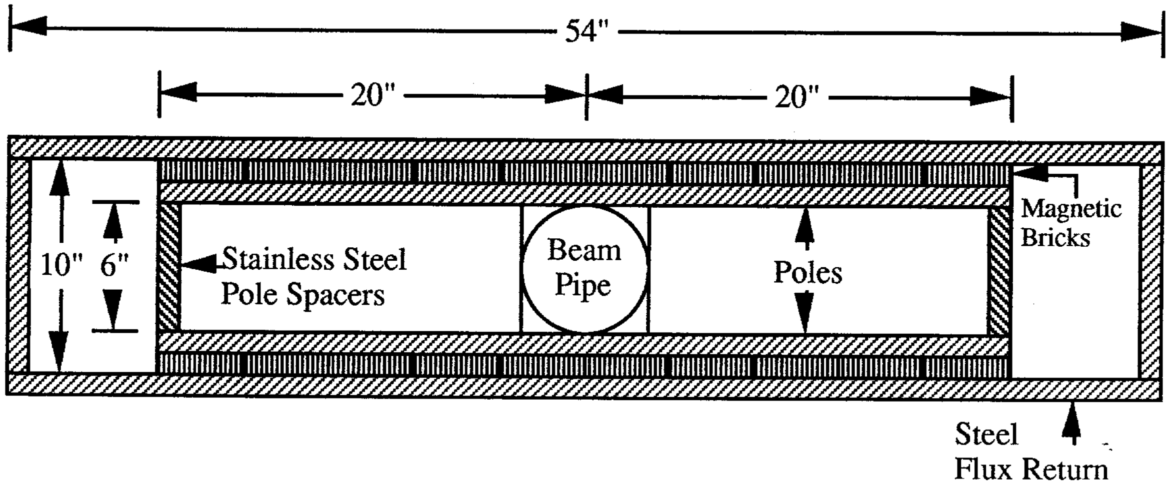

Figure 4: Electron inlet view of the dipole magnets showing the bricks stacked on either side of the poles in their 4" orientation.